Exploring the Practical Limits of Cooperative Awareness in Vehicular Communications

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Abstract—We perform an extensive study of cooperative awareness in vehicular communication based on periodic message exchange. We start by analyzing measurements collected on four test sites across Europe. To measure cooperative awareness, we use three metrics: 1) neighborhood awareness ratio; 2) ratio of neighbors above range; and 3) packet delivery rate. Using the collected data, we define a simple model for calculating neighborhood awareness given packet delivery ratio for a given environment. Finally, we perform realistic, large-scale simulations to explore the achievable performance of cooperative awareness under realistic transmit power and transmit rate constraints. Our measurements and simulation results show that: i) above a certain threshold, there is little benefit in increasing cooperative message rate to improve the awareness; higher transmit power and fewer messages transmissions are a better approach, since message delivery is dominated by shadowing. ii) the efficacy of cooperative awareness varies greatly in different environments on both large scale (e.g., 90% awareness is achievable up to 200 m in urban and over 500 m in highway) and small scale (e.g., vehicles in nearby streets can have significantly different awareness); iii) V2V and V2I communication have distinct awareness patterns; iv) each location has a distinct transmit power that achieves high awareness; and v) achieving high awareness levels results in increased reception of potentially unwanted messages; therefore, a balance needs to be found between awareness and interference, depending on the specific context. We hope our results will serve as a starting point for designing more effective periodic message exchange services for cooperative awareness.

Keywords—Cooperative Awareness, Empirical Evaluation, Vehicular Networks, Intelligent Transportation Systems, Periodic Message Exchange.

I. INTRODUCTION

Cooperative awareness is the ability to provide information on presence, position, direction, as well as basic status of communicating vehicles to neighboring vehicles (those located within a single hop distance) [1]. Enabled by periodic

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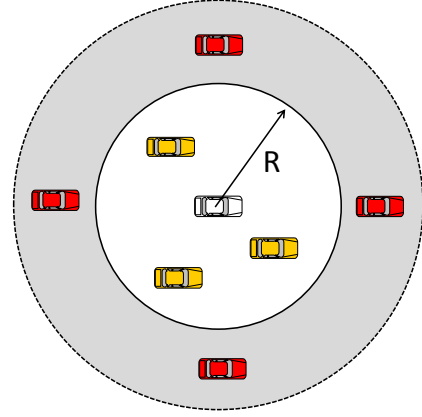
Fig. 1. Neighborhood awareness is based on the broadcast of periodic messages and allows gathering relevant information on the evolving neighborhood within a given range (e.g., the white zone with radius R). However, increasing awareness results in increased interference from distant vehicles (vehicles outside the designated awareness zone, i.e., grey unbounded zone), whose information might be less relevant than that of nearby vehicles.

message exchange, cooperative awareness is the basis for a large number of Intelligent Transportation Systems (ITS) applications proposed by standardization bodies [2]. Using the information provided by cooperative messaging, vehicles and Road Side Units (RSUs) are able to create a map of their surroundings, which is then used as input for safety applications that detect potentially hazardous situations. To enable cooperative awareness, standardization bodies have proposed specific messages for that purpose: in the EU, Cooperative Awareness Messages (CAMs) have been specified as part of the standard [1], whereas in the U.S., the same functionality is enabled by the Basic Safety Message (BSM) [3]. These messages are exchanged periodically and contain location, speed, and direction of the vehicle, among other information.

The IEEE 802.11p and ETSI ITS G5 standards were proposed in the US and the EU, respectively, as the underlying communication technology for Vehicle to Vehicle (V2V) and Vehicle to Infrastructure (V2I) communication. To understand the capability of these technologies to support awareness-based ITS applications, several research works have been conducted mostly resorting to analytical models or simulations. These studies demonstrate the capability of the vehicular communication system to support cooperative awareness in restricted conditions (e.g., low channel load) and that improved accuracy on awareness information comes at the cost of higher channel load and increased interference (e.g., [4]). Other

studies (e.g., [5],[6]) have shown that shadowing caused by vehicles, buildings or other objects, can impair the perform of single-hop broadcasting schemes. Adaptive power (e.g., [7]), rate (e.g., [4]) or joint power/rate (e.g., [8]) beaconing schemes can be used to improve network conditions, especially in high interference scenarios. However, previous research did not realistically study the performance limits of cooperative awareness in large-scale. Regarding empirical works studying cooperative awareness in Vehicular Ad Hoc Networks (VANETs), previous studies were limited to understanding the performance of communication system (e.g., using metrics such as packet delivery ratio [9]), and have neglected investigating the level of service provided to awareness-based ITS applications.

Our previous studies on the topic ([10], [11]) focused on measurement-based evaluation of cooperative awareness using the following three metrics: 1) Packet Delivery Ratio (PDR), a well established metric in the evaluation of communication systems, and two metrics to measure the efficacy of cooperative awareness; 2) Neighborhood Awareness Ratio (NAR); and 3) Ratio of Neighbors Above Range (RNAR). For completeness, we formally define all three metrics in Section III-A. In this paper, we extend those studies by:

- Developing and validating a simple model for calculating NAR, which requires as input only the information on PDR statistics of the desired environment; for a given environment and parameter settings (transmit power, rate), the model can provide the achievable awareness level as a function of distance;
- Analyzing how the duration of NAR measurement period t and the number of messages sent per period impact the performance of cooperative awareness.
- Performing large scale simulations – validated against measurements – to determine the achievable performance of cooperative awareness; simulations can determine required values for cooperative message transmit power and rate to achieve the target awareness at the target distance;

The rest of the paper is organized as follows. Section II discusses the related work. Section III describes the measurement-based aspect of the study, including the DRIVE C2X communications platform used to perform measurements, locations where measurements were performed, and the results of the measurements. Section IV details the model for calculating NAR using PDR, including the results of the comparison between measurements and model. Section V describes the results obtained through large-scale simulations, exploring the limits of cooperative awareness in terms of transmit power, rate, and target distance. Section VI concludes the paper.

II. RELATED WORK

Extensive research has been conducted to study cooperative awareness in VANETs, with most studies resorting to analytical models or simulations. While previous work has mainly focused on the assessment of communication performance, fewer studies looked at the cooperative awareness level provided to applications. In addition, the vast majority of previous studies

have focused solely on the evaluation of Vehicle to Vehicle (V2V) performance of periodic beaconing.

With respect to assessment of communication performance in Vehicular Networks using analytical studies or simulations, Mittag et al. [12] compared single and multi-hop broadcast performance. They concluded that limited benefit is achieved when using multi-hop communication instead of single-hop for cooperative awareness. Van Eenennaam et al. [13] verified analytically that the three main dimensions that make the solution space of beaconing in VANETs are transmission power, generation rate and message duration, and showed how different beaconing configurations support Cooperative Adaptive Cruise Control (CACC). Noori et al. [14] performed simulations to study the probability of beacon delivery in an urban scenario and showed how packet delivery is impacted by increasing vehicle density and different road types. In [4], Schmidt et al. study the trade-off between information accuracy and channel load derived from the dependable frequency of periodic beaconing. The authors also propose a scheme to control channel overloading by dynamically adjusting the beacon frequency to the current traffic situation (e.g., current vehicle density), while ensuring appropriate information accuracy. Kloiber et al. [15] analyzed the ability of cooperative message exchange to inform the vehicles about hazardous situations under challenging Medium Access Control (MAC) conditions. Several studies (e.g., [7], [8]) proposed improving awareness levels or reducing the channel load in VANETs by adaptive modification of beacon transmission power or generation rate. Yin et al. [16] consider multi-channel operation in their analytical studies and study the relevant impact of channel switching on the performance and reliability of safety message broadcasting on the Control Channel.

Regarding empirical evaluation of communication and application performance in VANETs, Martelli et al. [17] analyzed the Packet Inter-Reception time (PIR). Their results showed that PIR follows a power-law distribution (i.e., long-lasting outages occur with certain periodicity). Furthermore, PIR is strongly affected by Line of Sight (LOS) conditions, with up to five-fold performance drop in case of LOS obstruction by vehicles. Bai et al. [9] performed an extensive study on the impact of controllable parameters (transmit power, modulation scheme) and uncontrollable factors (distance, environment, velocity) on the performance of IEEE 802.11p radios in terms of PDR. In a similar study, Santa et al. [18] analyzed the influence of several parameters on the performance of CAMs using an experimental testbed and showed that the LOS conditions, equipment installation point and hardware capabilities are key variables in the network performance.

Apart from analyzing the conventional communication performance (e.g., throughput, delay), several studies proposed using information-centric metrics (e.g., awareness quality [12], [19], update delay [7], and PIR [8]). For instance, Kloiber et al. [7] proposed the *Update Delay* metric, which is defined for a pair of vehicles as the time interval between the expected CAM reception and the actual message reception. These metrics allow for a better understanding of the impact of the underlying vehicular communication system on application-level performance.

TABLE I.   TEST SITE ITALY RSU LOCATIONS

Id	Position (lat, lon)	Height	Installed
251	45.909728, 11.03248	9 m	Pole
252	45.905776, 11.02953	11 m	Overhead Gantry
253	45.86776, 11.005438	9 m	Pole
254	45.871724, 11.007555	9 m	Pole
255	45.8569, 11.000692	9 m	Overhead Gantry

III. MEASUREMENT-BASED EVALUATION OF COOPERATIVE AWARENESS

This section describes the metrics we use in our evaluation, DRIVE C2X experimental platform, the measurement test sites environments and the results of the measurement data analysis in terms of delivery rate (PDR), awareness (NAR) and interference (RNAR).

A. Performance evaluation metrics

1) *Packet Delivery Ratio (PDR)*: the ratio of the number of correctly received packets to the number of transmitted packets.
   Formally, for a transmitting vehicle, the combined PDR to all receiving vehicles within a certain distance range denoted by r (e.g., between 25 and 50 meters from receiving vehicle) is given by $PDR_{i,r} = \frac{PR_{i,r}}{PT_{i,r}}$, where $PT_{i,r}$ is the total number of messages sent by i to vehicles within r from i, whereas $PR_{i,r}$ is the subset of $PT_{i,r}$ packets that was correctly received. We measure PDR during the entire experiment duration, i.e., the time interval t over which PDR is measured equals the experiment duration. This metric provides the indication of the link quality and effective and maximum communication range. Effective communication range is defined as the maximum distance below which the PDR is above a given threshold (e.g., 0.9), whereas maximum communication range is the distance above which the PDR is equal to 0.

2) *Neighborhood Awareness Ratio (NAR)*: the proportion of vehicles in a specific range from which a message was received in a defined time interval. Formally, for vehicle i, range r, and time interval t, $NAR_{i,r,t} = \frac{ND_{i,r,t}}{NT_{i,r,t}}$, where $ND_{i,r,t}$ is the number of vehicles within r around i from which i received a message in t and $NT_{i,r,t}$ is the total number of vehicles within r around i in t (we use t=1 second). Referring to Fig. 1, for the white vehicle in the center, NAR is the proportion of nodes in the inner (white) circle (which encompasses the distance range from 0 to R) from which the observed vehicle received a message. This metric measures the efficacy of cooperative awareness messaging.

3) *Ratio of Neighbors Above Range (RNAR)*: for a vehicle i, distance R, and time interval t, the ratio of neighbors that are above a certain distance from the observed vehicle is defined as $RNAR_{i,R,t} = \frac{NA_{i,R,t}}{N_{i,t}}$, where $NA_{i,R,t}$ is the number of vehicles above R from which i received a message in t and $N_{i,t}$ is the total number of vehicles from which i received a message in t

(irrespective of distance from i). Referring to Fig. 1, for the white vehicle in the center, RNAR is the proportion of vehicles outside the inner (white) circle from which at least one message was received within t to the total number of vehicles from which a message was received. This metric gives an indication of potentially unnecessary traffic overheard from distant neighbors.

Note that, when representing PDR and NAR, we consider a set of uniformly spaced distance bins (i.e., an annulus – region between two concentric circles around the vehicle, represented by r). On the other hand, for RNAR we consider the region outside a certain radius R. Furthermore, note that t and R can assume different values, as these are application specific (e.g., $t = 1$ second might be sufficient for basic awareness service, whereas more stringent applications such as platooning might require $t \leq 100$ ms). Since the purpose of cooperative message exchange is timely notification of vehicles and infrastructure about existence of other vehicles, the NAR metric measures the proportion of vehicles in a given Region of Interest (ROI) that receive *at least one* message from the transmitting vehicle in time interval t and are thus aware of the transmitting vehicle. Conversely, the more distant the transmitting vehicle, the less relevant the messages from that vehicle are for majority of safety applications. To that end, the RNAR metric measures the proportion of vehicles outside the ROI R, from which the messages are received. In future scenarios, where a high percentage of vehicles will be equipped with the communication equipment, high RNAR would imply high interference, and thus low overall system throughput. Therefore, in terms of the communications performance, a well-functioning transmit system would aim to increase NAR, while at the same time keeping RNAR reasonably low.

B. Experimental platform

DRIVE-C2X project designed and evaluated a set of applications enabled by V2V and V2I communication in test sites throughout Europe. The DRIVE-C2X system uses ITS-G5 compliant radios that operate in the 5.9 GHz frequency band. The default value for transmit power was set to 21 dBm. On vehicles, whose heights ranged from 1.4 meters to 1.7 meters, omni-directional antennas were placed on the roof. Across test sites, vehicles had different communication system setup, including different radios, cable losses, antenna gains and placements, etc. All of these parameters resulted in significant variations of the effective transmit power output at each vehicle – this is in line with what is expected in the production-grade systems once the communication devices are installed in the cars due to different system designs across manufacturers. The radios transmit CAMs that are in line with the ETSI standard [1]. CAMs contain node information (e.g., position, speed, and sensor information) and are broadcast to one-hop neighbors over the control channel. Positioning information was provided by GPS receivers on the vehicles. In the analyzed datasets, CAMs were sent at 10 Hz frequency and had the size of 100 Bytes.

TABLE II.   DESCRIPTION OF MEASUREMENT TEST SITES AND PARAMETERS

Location	Gothenburg, Sweden	Helmond, the Netherlands	Tampere, Finland	Trento, Italy
Scenarios	Suburban (57.710316,11.94238)	Suburban (51.472803, 5.622418)	Suburban (lon < 23.847835, lat < 61.45894)	
	Highway (57.718424,11.918331)	Highway (51.477243,5.620085)	Highway (lat > 61.45894 and lat < 61.491023) (lon > 23.790289 and lon < 23.843118)	Highway (45.934435, 11.087010)
			Urban Otherwise	
Route Length (Max.)	11 km	5.5 km	22 km	60 km
Time	June 2013 (9 a.m. to 5 p.m)	September 2012 (9 a.m. to 5 p.m.)	April and May 2013 (7 a.m. to 1 p.m.)	July to October 2013 (7 a.m. to 2 p.m.)
Number of Vehicles	6	9	3	3/4
Vehicle Type	Personal	Personal	Personal	Personal
Antenna Type	Omni-directional	Omni-directional	Omni-directional	Omni-directional
Antenna Location	Rooftop	Rooftop	Rooftop	Rooftop
Antenna Height	approx. 1.55 m	approx. 1.44 - 1.66 m	approx. 1.5 m	approx. 1.49 m
Number of RSUs	0	0	0	5
RSU Antenna	N/A	N/A	N/A	Two Corner Reflector

C. Measurement test sites

The empirical evaluation of cooperative awareness in VANETs presented in this paper is based on analysis of logging information. All nodes (vehicles and RSUs) record all received and transmitted messages during the several test runs. In all test sites, vehicles were driven in normal traffic conditions with the presence of other vehicle types and respecting traffic rules. Traffic conditions (e.g., vehicle density) varied between test sites and trials but detailed information was not reported during field tests.

In test sites in Sweden and Finland, combined with antenna gains and cable losses, the effective vehicle transmit power ranged between 10 and 20 dBm. In Trento, Italy, there were 5 RSUs with the antenna placed at heights between 9 and 11 m at the positions and locations indicated in Table I. One RSU is installed on a highway on an overhead gantry 11 m above the road surface. It is equipped with two corner reflector antennas each having 14 dBi nominal gain, beam width 30 degrees in azimuth and 60 degrees in elevation. Remaining RSUs are installed next to the highway at the height of 9 m. Both vehicles and RSUs have a nominal output power of 21 dBm. Combined with antenna gains and cable and insertion losses, this yields 27 dBm transmit power on the vehicles, and 32 dBm on RSUs. These power settings are markedly higher than in remaining test sites, where the transmit power on vehicles was between 10 and 20 dBm. In the Netherlands, the vehicles used for testing were a combination of vehicles used in the other test sites.

In the test sites Sweden, the Netherlands and Finland, no logging data was available for RSUs, therefore the results contain V2V communication tests only. In Italy, on the other hand, logging data was available for both V2V and V2I communication. More details on the experimental setup are given in Table II.

D. Results

Below, we present and discuss the results of collected during the DRIVE-C2X measurement campaign in terms of PDR, NAR, and RNAR. The results are aggregated per vehicle (over messages transmission) and per test site (over different vehicles) for different environments (urban, suburban, and highway). Each distance bin is 25 meters for PDR and 50 meters for NAR and RNAR, with the plotted data point centered in the middle of the distance bin. Error bars represent one standard deviation around the mean of the measured variable for each vehicle. For statistical relevance, we consider solely bins with at least 40 data points. With respect to NAR and RNAR, for all results and plots shown in the following, one second window ($t = 1$ s) was used for determining the reception of messages from direct neighbors.

1) Packet Delivery Rate: Figs. 2 , 3 and 4 show the Packet Delivery Ratio (PDR) as a function of distance for V2V and V2I communications for different measurement locations.

V2V – As expected, for all test sites, the PDR decreases, albeit non-monotonically, as the node separation increases. The non-monotonic behavior of PDR over distance is mainly due to: i) in case of LOS communication, the dominating two-ray ground reflection model [20]; and ii) in case of non-LOS communication, variations in LOS obstruction level. Our results in terms of PDR are in line with the analytic results obtained by An et al. [19] and the empirical results by Visintainer et al. [21] for the highway scenario.

The PDR varies greatly between test sites and between qualitatively classified propagation environments. When considering the environment type, the communication ranges are increasing in the following order for a given test site: urban, suburban, and highway (e.g., see Fig. 2(c) and Fig. 2(d) for difference between highway and suburban PDR). The harsher propagation environment present in (sub)urban scenarios, including frequent non-LOS conditions due to surrounding objects (e.g., other vehicles, buildings, and trees), affects considerably the link quality and consequently the successful packet delivery. This is in line with previous measurements studies (e.g., [5]). However, the results for the same environment may vary substantially from one test site to another. This is most evident for the highway scenario where the maximum communication range varies from approximately 600 m in Sweden (Fig. 2(a)) and Finland (Fig. 2(f)) to more than 1000 m in Italy (Fig. 2(e)). This is the result of different propagation environments in different test sites (even for qualitatively same type of environment) as well as differences in installations in test vehicles (including antenna placement and gain). For example, one of the main reasons for the improved performance in the Italian test site (Fig. 2(e)) is the higher effective transmit power in test vehicles.

V2I – The V2I PDR results are presented in Fig. 4(a) and Fig. 4(b) for the Italian test site (highway scenario). These results are in line with the study by Paier et al. [22], with the increased PDR in case of our measurements due to higher transmit powers (32 dBm EIRP on RSUs and 27 dBm on
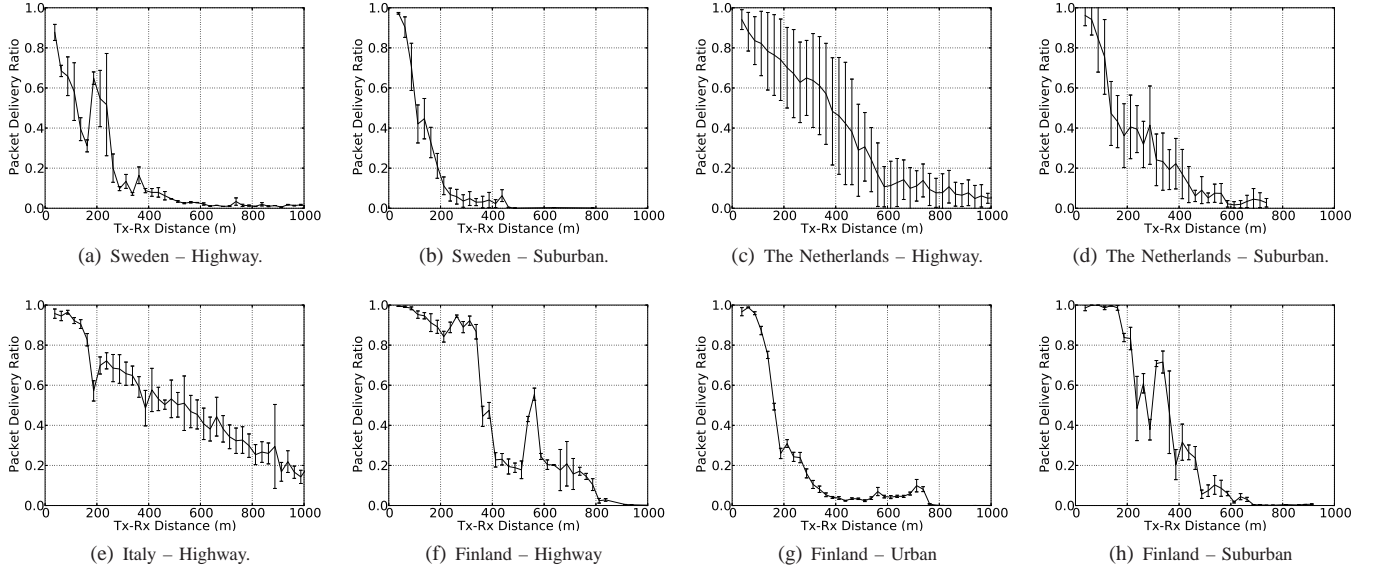
(a) Sweden – Highway.

(b) Sweden – Suburban.

(c) The Netherlands – Highway.

(d) The Netherlands – Suburban.

(e) Italy – Highway.

(f) Finland – Highway

(g) Finland – Urban

(h) Finland – Suburban

Fig. 2.   Overall V2V Packet Delivery Ratio (PDR) for Test Site Sweden, the Netherlands, Italy and Finland.

(a) The Netherlands – Highway.

(b) Italy – Highway
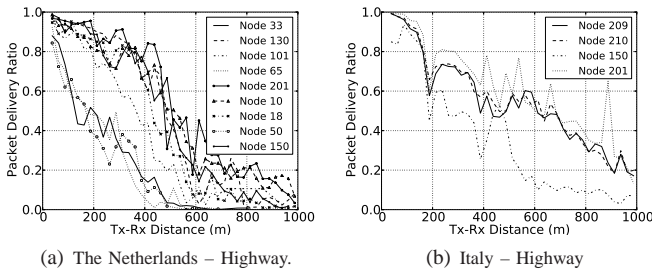
Fig. 3.   Per-vehicle V2V Packet Delivery Ratio (PDR) for Test Site the Netherlands and Italy.

(a) Overall V2I results

(b) Per-node V2I results (3 vehicles (201, 209, 210) / 5 RSUs 25x)
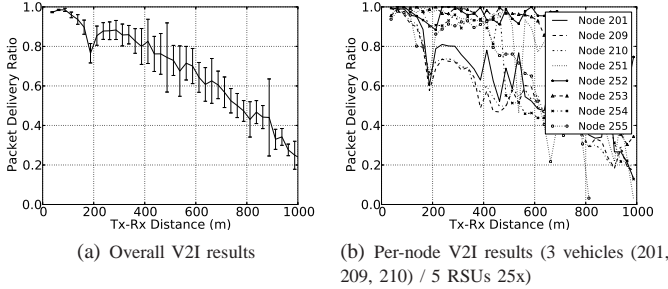
Fig. 4.   V2I Packet Delivery Ratio (PDR) for Test Site Italy.

vehicles, compared to 15.5 dBm in Paier et al.). Compared to V2V results in the same location (Fig. 2(e)), V2I PDR is significantly higher due to two main reasons: 1) advantageous position of RSUs (9-11 m above ground), giving the RSUs unobstructed LOS at larger distances; and 2) the increased effective transmission power of RSUs.

2) Neighborhood Awareness Ratio: Figs. 5, 6 and 7 present the NAR results for V2V and V2I communications in different locations. As evidenced in our previous work [10], there is a clear relation between PDR and neighborhood awareness.

V2V – Across test sites, the relationship between different environments and NAR is quite clear: the more complex the environment, the lower the NAR at a given distance. The most clear comparison can be seen on test site Finland (Table III and Figs. 5(f), 5(g) and 5(h)): in urban environment, 90% NAR can be achieved at a maximum of 200 m, compared to 350 m and 400 m in suburban and highway environments, respectively. Furthermore, looking more deeply at Fig. 5 we can see that qualitative separation of environments into urban, suburban, and highway cannot be generalized across test sites, which is in line with the PDR results discussed in Section III-D1. Therefore, a protocol that is able to dynamically adjust to the current environment would be useful for adapting the power of transmitted CAMs.

When analyzing the per-vehicle neighborhood results (Fig. 6), we can observe that, for a given distance bin, the performance fluctuations between different vehicles is pronounced in all scenarios. This is the result of both the environment changes over small distance as well as different system setup on vehicles (e.g., antenna placement, cable loss).

V2I – Results for V2I communications (Fig. 7) prove that the advantageous antenna positions and higher gain of RSUs antennas create a better propagation environment, which results in NAR that is above 90% up to 700+ m (Fig. 6(b)).

3) Ratio of Neighbors Above Range (RNAR): Figs. 8, 9 and 10 show the Ratio of Neighbors Above Range (RNAR) for different test sites.

V2V – RNAR exhibits an exponentially decreasing behavior, with progressively fewer vehicles detected at higher distances (e.g., proportion of vehicles above 400 meters mostly
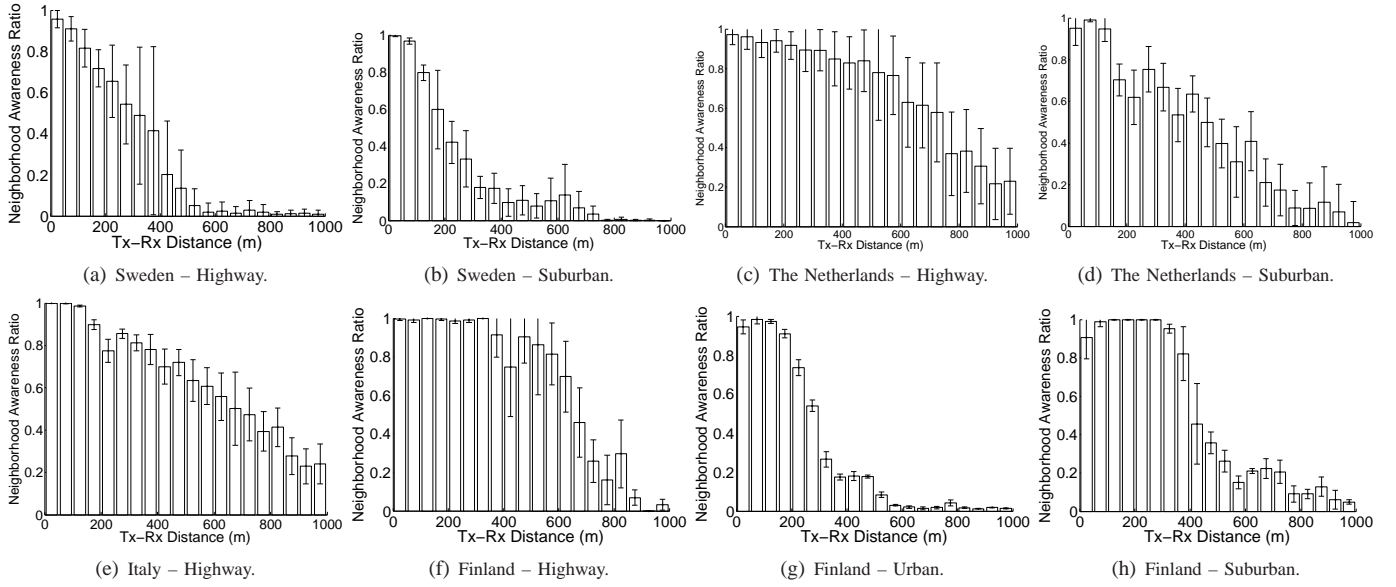
(a) Sweden – Highway.

(b) Sweden – Suburban.

(c) The Netherlands – Highway.

(d) The Netherlands – Suburban.

(e) Italy – Highway.

(f) Finland – Highway.

(g) Finland – Urban.

(h) Finland – Suburban.

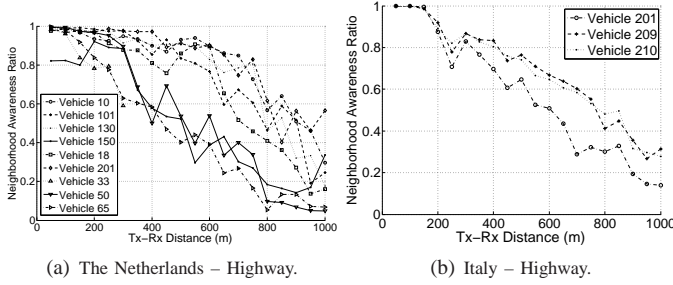Fig. 5.   Overall V2V Neighborhood Awareness Ratio (NAR) for Test Site Sweden, the Netherlands, Italy and Finland.

(a) The Netherlands – Highway.

(b) Italy – Highway.

Fig. 6.   Per-vehicle V2V Neighborhood Awareness Ratio (NAR) for Test Site the Netherlands and Italy.

(a) Overall V2I results.
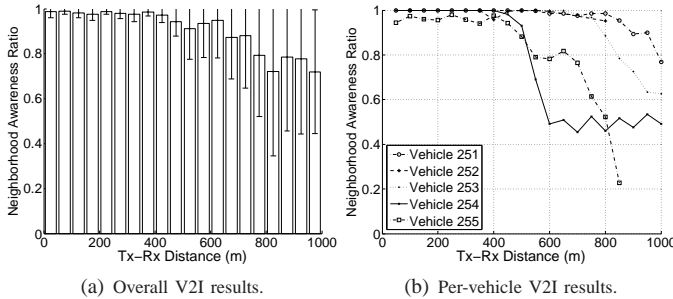
(b) Per-vehicle V2I results.

Fig. 7.   V2I Neighborhood Awareness Ratio (NAR) for Test Site Italy.

TABLE III.   DISTANCE ABOVE WHICH NEIGHBORHOOD AWARENESS RATIO (NAR) FALLS BELOW 90%

Environment	Sweden	The Netherlands	Finland	Italy
Highway V2V	100 m	250 m	400 m	200 m
Suburban V2V	100 m	150 m	350 m	N/A
Urban V2V	N/A	N/A	200 m	N/A
Highway V2I	N/A	N/A	N/A	650 m

contained within 10%). For safety applications requiring information from immediate neighborhood, such behavior is beneficial, since it implies that most periodic messages that a vehicle receives are useful. While the trend of RNAR is similar across the environments, different surroundings and effective transmit powers lead to significantly different RNAR values. For instance, for a highway scenario and a reference distance of 200 m, RNAR is 20% in Sweden (Fig. 8(a)) and 50% Finland (Fig. 8(f).

V2I – Whereas in V2V scenarios, the RNAR tapers off after at most 500 m, the large effective range of RSUs results in a large number of detected far-away vehicles (e.g., more than half of detected vehicles were farther than 500 m away in Fig. 10(a)). As explained previously, the large RSU range arises from their advantageous positions on tall gantries and higher-gain antennas.

4) Discussion: Measurement results show that V2V links with low effective transmit power can suffer from low neighborhood awareness, particularly in built-up urban areas; at the same time, V2I links can exhibit high awareness rates even above 1 km. On one hand, it is questionable if the neighborhood awareness information is relevant at distances above those required by safety-critical applications. High awareness is closely related to the potentially high interference, which reduces the frequency reuse and negatively impacts the throughput of future vehicular networks. On the other hand, within distances relevant for safety applications, there is a need for as high awareness as possible.

IV.   MODELING THE RELATIONSHIP BETWEEN COOPERATIVE AWARENESS AND PACKET DELIVERY RATE

In this section, we design a model that can provide insight into the effectiveness of future cooperative awareness. By using the information on PDR only, the model is able predict
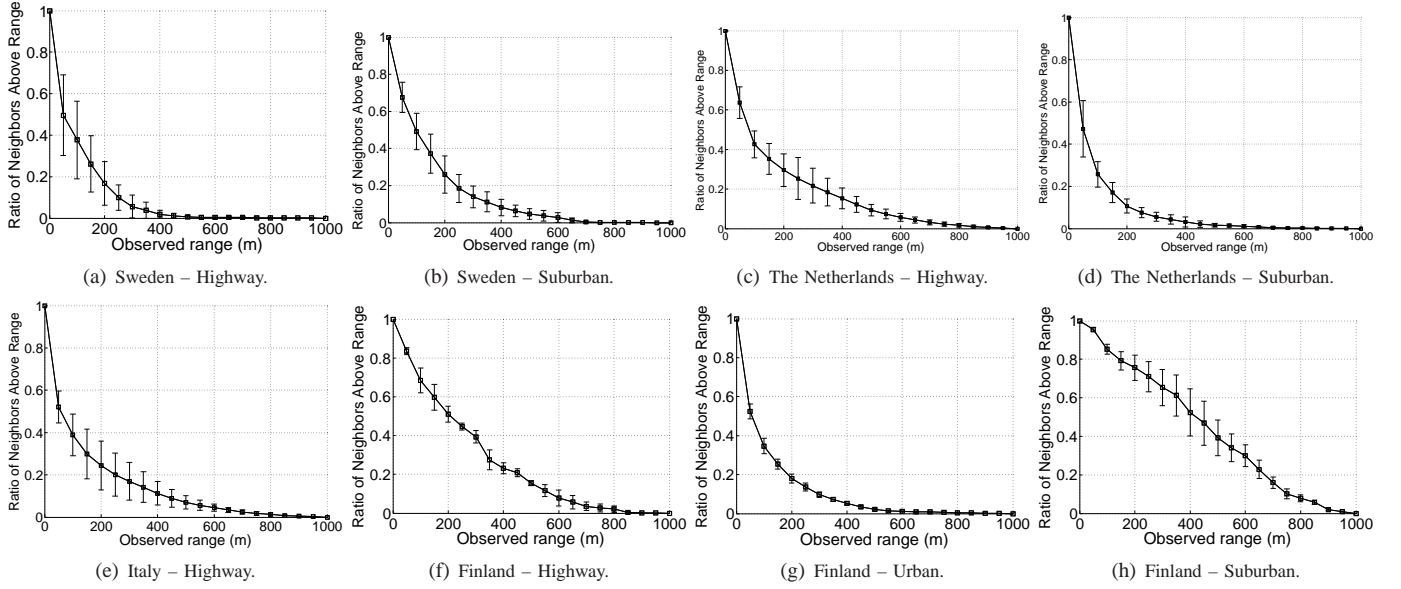
(a) Sweden – Highway. (b) Sweden – Suburban. (c) The Netherlands – Highway. (d) The Netherlands – Suburban.

(e) Italy – Highway. (f) Finland – Highway. (g) Finland – Urban. (h) Finland – Suburban.

Fig. 8. Overall V2V Ratio of Neighbors Above Range (RNAR) for Test Site Sweden, the Netherlands, Italy and Finland.
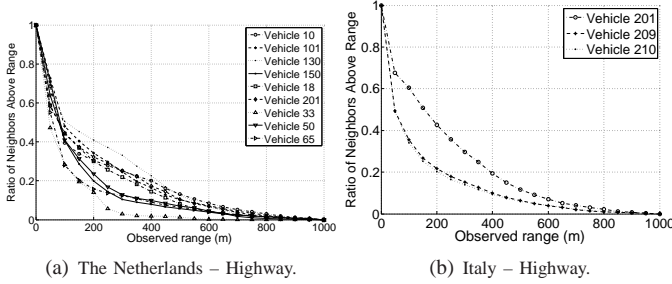

(a) The Netherlands – Highway. (b) Italy – Highway.

Fig. 9. Per Vehicle Ratio of Neighbors Above Range (RNAR) for Test Site The Netherlands and Italy.

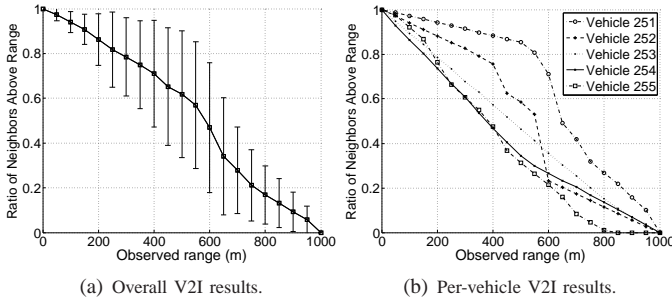(a) Overall V2I results. (b) Per-vehicle V2I results.

Fig. 10. V2I Ratio of Neighbors Above Range (RNAR) for Test Site Italy.

awareness in terms of NAR. In addition to giving system designers a quick insight into the effectiveness of cooperative awareness message exchange for a given environment, the model allows incorporating awareness into mathematical models for optimizing cooperative message sending.

We start by observing that the inter-reception time (IRT) of cooperative messages (i.e., the time interval between successful packet receptions) depends on the number of effectively lost packets. If the probability of packet reception p (which is tantamount to PDR) is assumed to be constant, IRT follows a geometric distribution [8]:

$$P(IRT = k) = (1-p)^{k-1}p \qquad (1)$$

NAR is defined as probability of receiving *at least* one message from a vehicle in time t (see Section I). In other words, *at least* one out of N sent messages in time t needs to be received to make the receiving vehicle aware of the sending vehicle. Therefore, we model NAR using the cumulative geometric distribution over the number of CAM transmissions, where the probability of success for each CAM transmission is equal to the PDR for distance r, PDR_r:

$$NAR_{r,t} = \sum_{k=1}^{N} (1 - PDR_r)^{k-1} \times PDR_r. \qquad (2)$$

The above expression can also be written in terms of the probability that all messages in time t from the transmitting vehicle fail to reach the designated recipient:

$$NAR_{r,t} = 1 - (1 - PDR_r)^N. \qquad (3)$$

However, geometric distribution assumes independent trials (i.e., independent CAM transmissions). In reality, measurements have shown that there is a correlation between subsequent CAM transmissions, provided that the time between successive transmission is sufficiently small (e.g., below one second). In other words, probability of success in time t increases if the transmission in time $t-1$ was successful: $P(CAM_t|CAM_{t-1}) > P(CAM_t)$. Analogously, the probability of success of CAM reception decreases if the previous CAM transmission failed: $P(CAM_t|\overline{CAM_{t-1}}) < P(CAM_t)$. This observation was confirmed by previous measurement
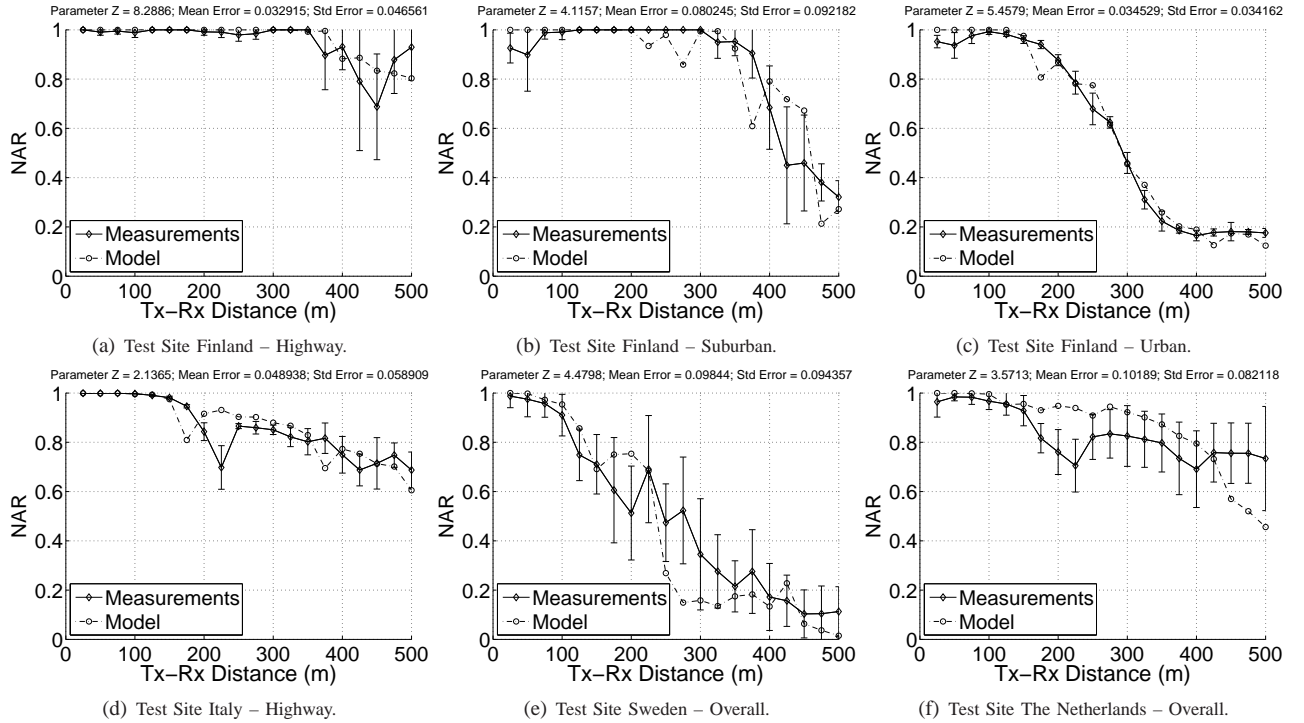
Fig. 11. Neighborhood Awareness Ratio (NAR) results: measurements vs. model. Mean and standard error is expressed in terms of absolute difference in NAR between the measurements and the model. The error bars for the measurement data represent one standard deviation around the mean.
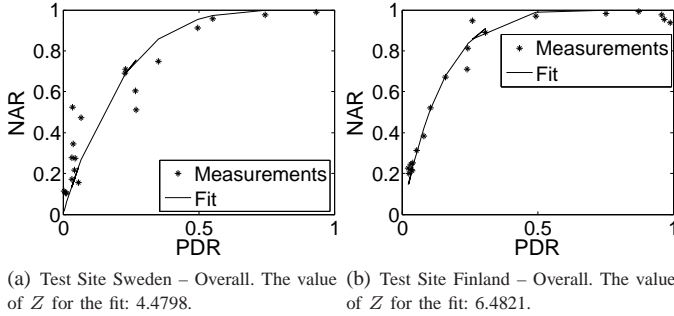

Fig. 12. Relationship between PDR and NAR.

studies reported by Martelli et al. [17] and Bai et al. [23]. This dependency affects the cooperative awareness and consequently the NAR calculations. Since NAR does not benefit from bursts of received messages (e.g., receiving one message in t is equal to receiving 10 messages in t in terms of NAR), we need to implement a "discount" function to the cumulative geometric distribution to account for the negative effect (loss bursts) in the calculation of NAR. This can be seen as reducing the effective number of transmissions to achieve awareness. Thus, we consider

$$NAR_{r,t} = 1 - (1 - PDR_r)^Z, \qquad (4)$$

where $Z \leq N$.

To estimate Z for different environments, we compared PDR and NAR results from measurements described in section III.

Using a non-linear MMSE estimator, we fit the value of Z in eq. (4) for each of the datasets. Fig. 12 shows the relationship between PDR and NAR for two measurement test sites, whereas Fig. 11 shows the resulting NAR estimation using eq. (4) and fitted Z parameter, compared with the measured NAR. The relatively large range of Z values (between approx. 2 and 8) can be explained by analyzing Fig. 13, which gives some indication of this relationship: with the fixed CAM transmission rate of 10 Hz, the figure shows that, by increasing the number of sent messages above a certain threshold (in this case, 200 ms period equivalent to 2 messages per time period), the increase of NAR is quite limited. Therefore, if there are at least two messages in the observed time slot t, i.e., $Z \geq 2$ in eq. (4), the results do not change considerably (e.g., see results for 200 ms to 2 seconds time slots in Fig. 13). These results go in line with the conclusion that the CAM transmissions succeed (and fail) in bursts due to the communication being dominated by shadowing; if there are at least two messages sent in a time period t, sending additional messages results in little benefit (two as opposed to one, in order to counter: i) no messages reaching the receiver on time due to queuing or processing delay at either the transmitter or receiver; and ii) sudden message loss due to small-scale fading). We further explore this topic through simulations in Section V.

In terms of the accuracy of the model, Fig. 11 shows that the model matches the measurements better when the data is separated according to environments (e.g., urban, suburban, highway). The main reason is that the behavior of PDR for separate environments is less variable than when PDR results
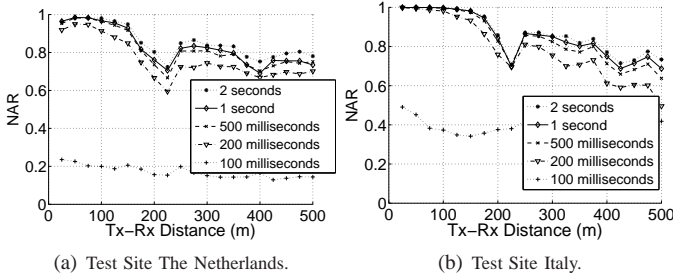
Fig. 13. Behavior of Neighborhood Awareness Ratio (NAR) with varying time period t. Since CAM messages were sent with 10 Hz frequency, the time periods t of 100 ms, 200 ms, 500 ms, 1 s, and 2 s contain 1, 2, 5, 10, and 20 CAM transmissions, respectively.
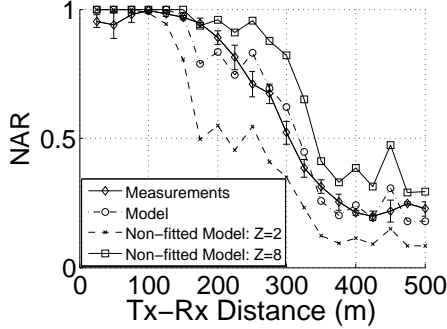

Fig. 14. NAR results for Test Site Finland: measurements, results from model generated using best-fit Z value (4.2768), Z=2, and Z=8.

are combined (see, for example, Fig. 2 and related figures). Figs. 11(a)-11(d) show that NAR generated by the model is very close to measured values. On the other hand, results for combined environments (e.g., Fig. 11(e) and 11(f)), the estimate is not as accurate, particularly at distances larger than 200 m. The main reason for this is that combining results from different environments increases the variation of PDR used for calculating NAR in eq. (4), particularly at larger distances. Furthermore, the range of values for Z is relatively large (2-8); this confirms the results shown in Fig. 13: while a single message sent in a time period is not sufficient, the difference between having two or more transmitted messages per time period t is comparatively small.

A practical application of the model is providing upper and lower bound for awareness. For instance, for Test Site Finland, Fig. 14 shows the fitted ($Z = 4.2768$) and non-fitted model results for Z equal to 2 and 8. The curves for non-fitted model encompass the measured NAR curve, while not being overly wide to render them obvious. Therefore, when actual measurements of NAR are not available to fit the parameter Z, the theoretical model can be used to give a relatively confident range of NAR values based on PDR measurements only.

To conclude, the simple model we developed in this section can estimate NAR by knowing PDR behavior over distance for a given environment. While it is not able to account for all the effects that impact cooperative awareness, the model can give an insight into the behavior of awareness in an environment for which PDR is available.

V. LARGE SCALE SIMULATION OF COOPERATIVE AWARENESS

The measurement results presented in Section III provide valuable insights into the performance of cooperative awareness under realistic conditions, by considering different environments, V2V and V2I communication, different vehicle setups (antenna, effective power), etc. However, the measurements analyzed in Section III are limited in scale (e.g., the number of communicating nodes is below 10 on all test sites) and scope (e.g., CAM transmit rate and power were fixed).

In this section, we resort to realistic simulations to study the achievable performance of cooperative awareness by varying the transmit rate and transit power of CAM messages in scenarios containing thousands of vehicles in different environments. The main questions we aim to answer in this section are: 1) to increase awareness in a given environment, is it better to transmit more CAM messages at lower power or fewer messages at higher power? 2) how many CAM messages do we need to transmit before gains are diminished? 3) given realistic transmit power limitations, what is the largest distance at which high levels of awareness can be achieved for a specific environment? 4) for the same transmit power and rate settings, how significant are the differences between urban and highway environments?

A. Simulation Platform

Measurements described in Section III showed that PDR, NAR, and RNAR are highly dependent on the propagation environment where V2V communication occurs. Therefore, simulating cooperative awareness requires a simulation tool that is able to represent distinct propagation environments (e.g., urban intersection, rural highway, urban canyon). For that reason, we used Geometry-based Efficient propagation Model for V2V communication ($GEMV^2$), a freely available V2V propagation model and simulation framework (see [6]) to perform a realistic assessment of cooperative awareness on a large-scale. $GEMV^2$ is an efficient geometry-based propagation model for V2V communications, which explicitly accounts for surrounding objects (buildings, foliage and other vehicles). The model considers three V2V links categories, depending on the LOS conditions between transmitter and receiver, to deterministically calculate large-scale signal variations (i.e., path-loss and shadowing):

- Line of Sight (LOS): links that have an obstructed optical path between the transmitting and receiving antennas;
- Non-LOS due to vehicles (NLOSv): links whose LOS is obstructed by other vehicles;
- Non-LOS due to buildings/foliage (NLOSb): links whose LOS is obstructed by buildings or foliage.

Additionally, $GEMV^2$ determines small-scale signal variations using a simple geometry-based stochastic model that takes into account the the number and size of surrounding objects. The simulator allows importing realistic mobility data from Simulation of Urban MObility (SUMO) [24] and building/foliage outlines from OpenStreepMap (http://www.openstreetmap.org/).

Fig. 15. Urban environment (Porto, Portugal) used for simulations. The map overlay shows the number of directly reachable vehicles ("neighbors") for each vehicle, as generated by the $GEMV^2$ model. For each vehicle, the colored bar represents the number of neighbors. Warmer and taller bar colors indicate more neighbors.

(a) Highway Porto. (b) Urban Porto.

Fig. 16. Std. dev. of 10 Hz CAM distribution.

(a) Test Site Finland – Highway. (b) Test Site Finland – Urban.

Fig. 17. Comparison of NAR results: measurements vs. simulations. The error bars represent one standard deviation around the mean.

B. Simulated environments

To evaluate the behavior of cooperative awareness in different environments, we performed simulations in $GEMV^2$ using roadways and geographic data from highway and urban locations in and near the city of Porto (i.e., the same locations as those in the measurements reported in [6]) [1]. Received power distributions for cooperative messages was based on the measurements in the same location (as explained in Section. V-C). Specifically, we simulated two distinct environments:

- Urban environment, a core part of the city of Porto containing 2410 vehicles delimited by a rectangle with the following coordinates: (41.1426,-8.6850),(41.1624,-8.6203). The area is shown in Fig. 15 and contains 2410 vehicles.
- Highway environment, comprising a 12.5 km stretch of A28 Highway with approximate center coordinates at (41.2327, -8.6954) and containing 404 vehicles.

To ensure credible locations of vehicles, we used vehicle locations collected through aerial photography (details on the datasets are available in Ferreira et al. [25]).

C. CAM message received power and inter reception times

To generate realistic small-scale signal variation and inter reception times for cooperative messages, we used the data collected during V2V measurements. Specifically, we used the standard deviation of received power for cooperative messages collected in the study by Boban et al. [6]. The measurements were made using ITS-G5 compliant radios (NEC LinkBird MX) operating in the 5.9 GHz frequency band. The messages were generated at 10 Hz frequency and exchanged by passenger cars traveling in Porto (urban environment) and on surrounding highways.

Since message inter-reception times are directly dependent on the successful packet decoding at the receiver, we used the received power variation measured in V2V experiments to generate realistically simulated inter-reception times. Specifically, for the two environments (urban and highway), we divided the measurement data into one second bins and calculated the standard deviation of received power for each bin. We excluded the

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[1]Received power level measurements were not available for the Test Sites of the empirical evaluation study described in Section III-C.
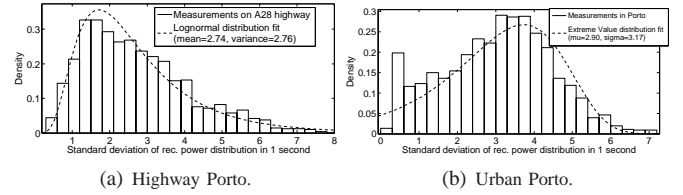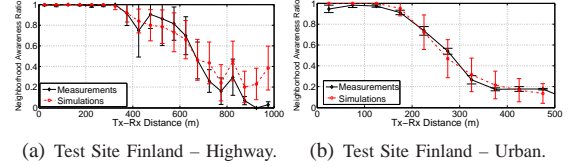
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bins with PDR below 50% to ensure a minimum of five messages per bin. We fit the measured standard deviation across the entire measurement dataset to the theoretical distribution functions available in MATLAB Distribution Fitting tool. The measurement data and the corresponding fits are shown in Fig. 16. Finally, we modified the small-scale signal variation model in $GEMV^2$ so that it draws a random number from the corresponding best-fit theoretical distributions (Fig. 16), representing the standard deviation of received power for each one-second bin. The generated small-scale variation is then added on top of the received power calculated by large-scale signal variation model.

D. Validation of simulation results against measurements

Before performing the large-scale simulations, we wanted to validate our simulation model against the small-scale measurements. For that purpose, we used comparable simulated environment (including area size and road layout), effective transmit power, vehicle types, and cooperative message generation rates to those where measurements were performed in Test Site Finland. Fig. 17 shows the results of the comparison in terms of NAR. The results for both highway and urban comparison are quite similar. The larger standard deviation for simulated urban environment can be explained by simulated vehicles taking more diverse routes (the number of simulated vehicles was 2000 compared to 3 vehicles used for measurements), thus experiencing a larger number of distinct propagation environments. The reason for the discrepancy above 800 meters in highway environment is that the simulated location, while similar to the Test Site Finland Highway, is not completely identical to it.

E. Simulation Results & Discussion

In this section, we study the behavior of NAR by varying the transmit power and transmit rate of cooperative messages in urban and highway environments. We note that, in simulations, we do not consider interference generated by CAM exchange; therefore, the results in this section are an upper bound of

awareness performance for the given transmit power and transmit rate. Also, note that the simulation results were generated with the assumption of -95 dBm receiver sensitivity threshold, in line with the sensitivity of devices used for DRIVE C2X measurements; given different receiver sensitivity thresholds of radios, the results we show in this section would be equivalent to changing the transmit power level by the same amount (i.e., NAR would be increased by the same amount by increasing sensitivity by 1 dB or by increasing transmit power by 1 dBs).

1) Urban Environment: Figs. 18 and 19 show NAR as a function of CAM transmit rate and transmit power, respectively, over distance. Fig. 18(a) shows that, at 5 dbm effective transmit power, awareness above 90% can be achieved only up to 50 m, irrespective of the CAM rate. For 15 dBm and 23 dBm, 90% awareness is achievable at 200 m and 300 m, respectively (Fig. 18(b), 18(c)). Similar to what we observed in measurements (Fig. 13), NAR increase can be noticed when going from the rate of one CAM per time period to two and three; increasing the rate further results in minimal benefits. On the other hand, increasing power has a direct influence on the awareness. Fig. 19 shows how NAR increases with power; it is interesting to see that, for each distance, there is a relatively narrow range of transmit powers at which the awareness "transition" occurs, i.e., where NAR increases rapidly with each 1 dB power increase. As noted before, increasing the CAM frequency has little effect on the modification of the transition zone.

2) Highway Environment: In highway environment, compared to urban, we observe a notably higher NAR for the same distance and CAM transmit power and rate[2]. While this is to be expected, it is interesting to note that the transmit power and rate required to reach 90% NAR at 400 m is approximately 20 dB and two CAM transmissions per period (Fig. 21). This shows that production-ready DSRC radios, often limited to 23 dBm EIRP, have the ability to provide high awareness in highways. To achieve the same performance in urban would require over 33 dB EIRP (Fig. 19), which is not allowed according to the current transmit power limits in the US and EU [26]. With realistic limits in mind, our results show that high awareness (above 90%) for urban environment can be achieved up to 250 m. Furthermore, similar to results for urban, the transition from low (sub-20%) to high (above 90%) NAR on highway requires a limited range of transmit power values (8-10 dB difference in Fig. 21 compared to 5-7 dB in Fig. 19), albeit at different absolute transmit powers (up to 15 dB in highway, compared to 35 dB in urban). These results indicate that, for each location, there is a specific transmit power level that is sufficient for achieving high awareness for a given distance. However, since each location has a distinct propagation pattern (compare, for example, Fig. 19 and Fig. 21), determining the correct power for a given environment requires adaptive power control algorithms (e.g., [8], [27]).

In both environments, there is virtually no difference in terms of NAR for 5 Hz and 10 Hz CAM rate (Figs. 19(b) and 19(b) for urban, Figs. 21(b) and 21(c) for highway);

this agrees with the measurement results shown in Fig. 13. Therefore, we conclude that transmitting more than approximately two to four messages per time period does not result in improved awareness, while at the same time increasing the channel load[3].

In our simulations, we did not observe any significant impact of vehicle density on NAR for a given distance. This is in line with the assumptions that the model makes in Section IV, as well as the comparison between simulations and measurements (Fig. 17), where NAR within a given distance range did not depend on the number of the vehicles; on the other hand, NAR does depend on the environment and distance between vehicles. However, we should highlight that we do not account for interference in our simulations; when considering interference between nodes, we expect vehicle density to have a considerable impact on the awareness level at high channel load values.

VI. Conclusions

Periodic broadcast of single-hop cooperative messages is the basis for future cooperative ITS systems in the EU, US, Japan, and other markets. Through measurements and simulations, we analyzed the ability of periodic message exchange to enable cooperative awareness as well as their impact on channel load. First, we empirically evaluated the performance of cooperative awareness using measurements collected in four test sites in Europe within the scope of DRIVE-C2X project. The measurements were performed in three distinct environments (urban, suburban and highway) and between vehicles (V2V communication) and vehicles and infrastructure (V2I communication). Next, we developed a simple model to estimate cooperative awareness for an environment, provided that PDR information is available. The model can be used to define upper and lower bound of achievable awareness and to get insight into the performance of cooperative awareness in a given environment. Finally, we performed large-scale simulations with thousands of vehicles in urban and highway environments to explore the limits of cooperative awareness, given the practical limitations in terms of transmit power and rate of periodic messages.

Our results demonstrate that cooperative awareness is strongly dependent on link quality and propagation conditions. The propagation environment where vehicles move determines the maximum achievable communication range and neighborhood awareness: the more complex the environment, the lower the awareness. With respect to the link type, the results show that the advantageous positions of RSUs improve the awareness levels for V2I communications when compared with V2V communications. Furthermore, higher effective transmit power can, while increasing awareness levels, also (prohibitively) increase the interference by far-away nodes; this effect is

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[2]Somewhat higher variability in of NAR in highway is a result of a smaller number of simulated vehicles compared to urban (404 vs. 2410).

[3]Note that the message rate required to reach a certain NAR is not tied to a time period of specific duration, but to the number of messages per time period t (eq. 4): if, for example, t is one second (as is the case in our measurements and simulations), then the rate is considered per one second; if an application requires awareness within 100 ms, the rate should be considered per 100 ms. This relationship holds for sufficiently small time periods (e.g., up to a few seconds).
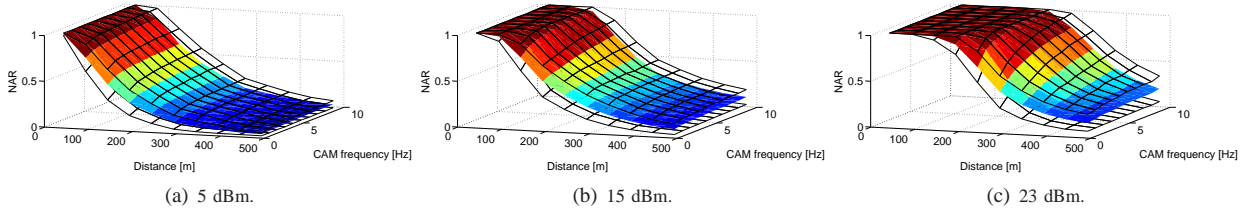
Fig. 18.   NAR simulations in urban environment: CAM rate varied, Tx power fixed to 5, 15, and 23 dBm. Mean value is represented by the surface; standard deviation is represented by the black grid.
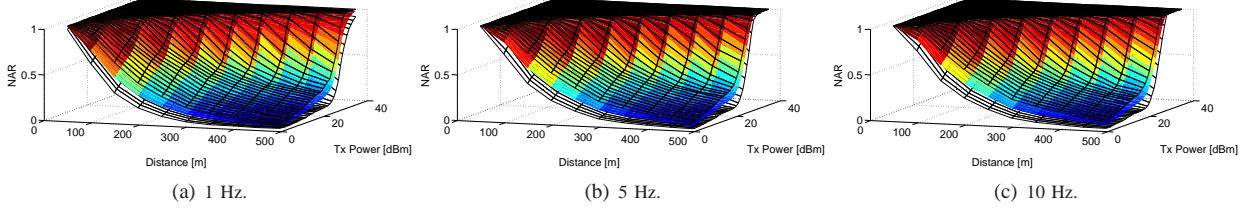

Fig. 19.   NAR simulations in urban environment: Tx power varied, CAM rate fixed to 1, 5, and 10 Hz. Mean value is represented by the surface; standard deviation is represented by the black grid.
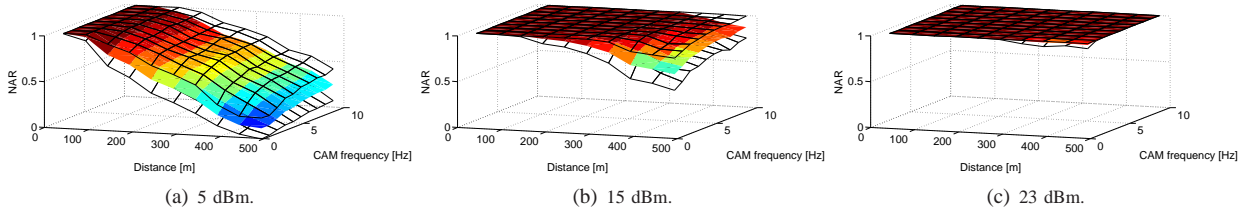

Fig. 20.   NAR simulations in highway environment: CAM rate varied, Tx power fixed to 5, 15, and 23 dBm. Mean value is represented by the surface; standard deviation is represented by the black grid.
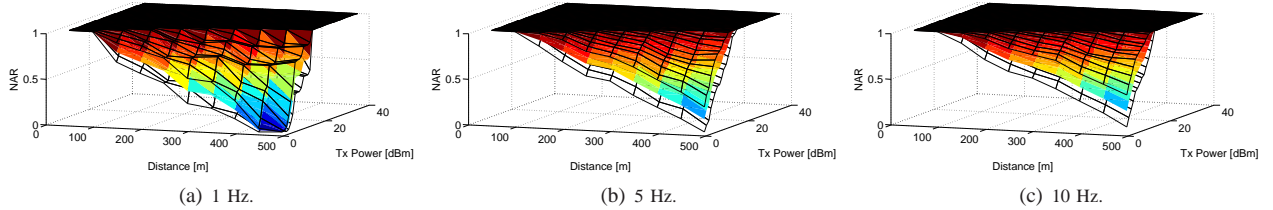

Fig. 21.   NAR simulations in highway environment: Tx power varied, CAM rate fixed to 1, 5, and 10 Hz. Mean value is represented by the surface; standard deviation is represented by the black grid.

especially evident for V2V communication in highway scenarios and V2I communication in general. Furthermore, both measurements and simulations showed that increasing transmit power has a much more significant impact on awareness than transmit rate. In fact, irrespective of the environment, above a certain transmit rate per observed time period (upper-bounded by three to four messages), increasing the rate results in minimal improvement of awareness, while at the same time increasing the channel load.

With regards to the application performance, our results show that applications requiring high awareness levels (e.g., 90%) up to 100 m can be satisfied in virtually all environments. For larger distances, high awareness is possible in certain types of environments (e.g., highway), whereas in others the awareness is limited by the harsh propagation environment and regulatory limits on transmit power level (this is the case above 200 m in typical urban environments). Furthermore, transitions between environments incur a significant difference in awareness; therefore, it is beneficial for applications to dynamically detect and adapt the parameters (e.g., transmit power) according to the current surroundings. We hope our results regarding the benefits and practical limitations of cooperative awareness message exchange will help in the design of future safety and efficiency ITS protocols and applications.

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